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Title: DIRECT LASER INITIATION OF PETN

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DIRECT LASER INITIATION OF PETN

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ABSTRACT

In the early 1970s Yang and Menichelli demonstrated that direct laser illumination of low-density secondary explosive pressings through a transparent window could produce detonation. The energy requirement for threshold initiation of detonation was reduced when a thin metal coating of metal covered the side of the window against which the low-density explosive was pressed. We have obtained experimental results that are in general agreement with the results of Renlund, Stanton and Trott (1989) and recent work by Nagayama, Inou and Nakahara (2001). We report exploration of the effects of laser beam diameter, PETN density and specific surface area, and thickness of a titanium coating on the window.

1. Introduction

This report presents the results of a continuing series of tests to define the performance of a direct laser initiation process to detonate PETN, a secondary explosive. The driving force for initiation is a laser-induced plasma, confined between the explosive and an optically transparent fused-silica substrate. A thin coating of metal is typically applied to the explosive side of the silica substrate to enhance light-energy absorption and the efficient production of hot plasma. Renlund et al.[1] had previously performed similar experiments and measured initiation dependencies upon laser-related parameters such as pulse duration, peak power, mode structure, spot size and coating thickness, and explosive parameters, such as density and specific surface. The current work was motivated by an interest in reducing the firing energy, if possible, and determining whether detonators based upon laser stimulus might be designed so as to be simple, reliable and easily fabricated.

2. Objectives

The primary objective of the experimental program was to define the initiation threshold for PETN explosives under direct illumination by short-duration laser light pulses under various conditions of laser pulse energy, peak power density and spot size. A Neyer analysis[2] was used to evaluate the initiation threshold. The time interval between the laser pulse and arrival of a detonation wave at the end of the explosive sample was monitored for some of these tests.

3. Experimental Approach

3.1 Explosive Preparation

Two types of PETN were utilized in this study — high specific surface area (HSSA) PETN with a specific surface of 25,000 cm^2/g and medium specific surface area

PETN (MSSA, 12,000 cm^2/g). Each was pressed into a flanged, 0.005-in.-wall aluminum cup to produce an explosive column 2.23 mm in length by 7.24 mm in diameter. Two densities of PETN were utilized in the experiments, 0.90 and 1.00 g/cm^3. The process used to prepare samples is described in Section 3.3.

3.2 Laser Window

The fused-silica substrates used to confine the optically generated plasma were 7-mm in diameter and 0.012-in.-thick, and were manufactured by Continental Optics Inc. Most of the windows were coated with a thin layer of titanium, which adheres well to silica and provides a light-energy-absorbing layer that enhances plasma production. Two coating thicknesses were utilized, 1550 and 2350 Angstroms. These windows were installed against the PETN explosive with the coated side in contact with the explosive surface. Some of these initiation tests were conducted with no coating applied to the silica substrate.

3.3 Explosive Fixture

A special aluminum fixture was fabricated to hold the PETN-filled cup and laser window. The fixture consisted of three components:

1) a lower aluminum plate with a central hole bored to a close fit diameter to receive the explosive-filled cup,

2) an upper plate used to hold the flanged cup and window in place and

3) a screw- in plug to make contact with the outer edge of the laser window. The plug also contained a central 4-mm-diameter hole to permit laser illumination of the explosive. This fixture is shown in Fig 1. The laser window was placed on top of the exposed PETN.

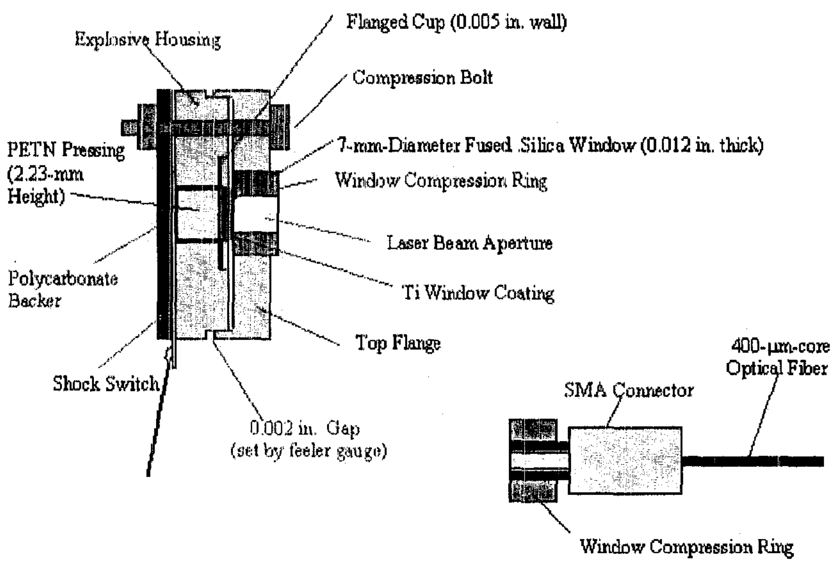

Figure 1. Test Fixture

During assembly of this fixture, the laser window was pressed a fixed distance (0.002 in.) into the low-density PETN. This assured contact between the window surface and the explosive and provided final pressing of the explosive to the desired density (either 0.90 or 1.00 g/cm^3). This pressing was achieved by the tightening of three bolts, after the window compression ring had been screwed in to make light contact with the periphery of the laser window. When the 2-mil gap between upper and lower plates was closed, the pressing operation was complete and the explosive was ready to be tested. As an option, a Kapton shock switch could be attached and compressed into the back of the fixture by a 1/8-in.-thick polycarbonate backing plate. Its function was to monitor detonation wave breakout from the bottom of the explosive cup.

The explosive fixture was mounted within a ring inside an explosive test chamber containing a1-in.-thick Plexiglas window to permit entry of the laser light. All other instrumentation for these tests was located external to the test chamber. Shock switch connecting wires were run out of a slot in the chamber wall for oscilloscope attachment.

3.4 Laser System

Much of this work utilized direct illumination of the explosive or substrate coating to light pulses obtained from a solid-state Nd:YAG laser operating at a wavelength of 1064 nm. A Model 103 Laser Photonics laser, providing either a near-Gaussian or multimode output with 15-ns-duration (FWHM) light pulses, was used in this investigation. The experimental configuration is shown in Fig 2. A plano-convex lens of various focal lengths was used to focus the laser output to differing spot sizes upon the explosive/coating surface. A beam attenuator consisting of a half-wave plate and polarizer analyzer was used to control laser pulse energy. This type of attenuator provides adjustable light energy throughput with no alteration to the laser mode or pulse length. The maximum laser pulse energies obtained were 120 mJ multimode, or 25 mJ with a near-Gaussian distribution.

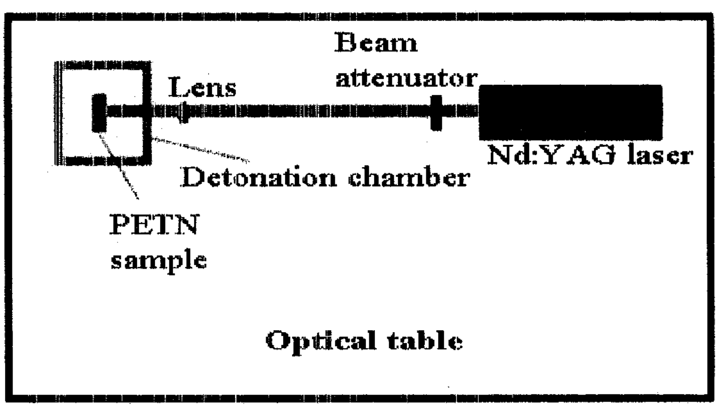

Figure 2. Optics for Direct laser Initiation Experiments

For some of these tests, fiber transport of the laser output was utilized to provide a more uniform, top-hat-like distribution of laser light at the explosive/coating surface. Fibers with a core diameter of 400 μm and 3-m length were used. Each end of the fiber was fitted with a connector. To permit attachment of the fiber, the screw-in plug assembly of the explosive test fixture was modified for a SMA-type fiber connection. This is shown in the sketch contained in the lower left-hand side of Fig 1. Attachment of the fiber to the explosive fixture was made after window compression was performed. When connected to the plug assembly, the end of the fiber contacted the window substrate. Laser light output from the fiber was allowed to diverge through the substrate before illuminating the explosive/coating, providing a laser spot about 30% larger than the core diameter of the fiber.

Injection of multimode laser light into a fiber was achieved using a 20-cm focal-length lens. The output energy of the fiber was set prior to fiber attachment. Fiber output energies up to 50 mJ within a 15-ns pulse duration were transmitted without damage to the fiber. Attachment of the fiber to the explosive test fixture was made after the fixture was mounted within the test chamber. Entry of the fiber into the test chamber utilized a slot within the chamber wall. Two opposed, 3-in.-radius fiber bends were required for chamber entry.

Initiation-threshold measurements were guided by a Neyer analysis procedure, which specified sequential laser energy settings. The number of tests conducted for each set of experimental conditions was typically 10-12 due to the limited quantity of explosive cups and windows available. This usually was a sufficient number to incur initiation crossovers but limited the precision of the threshold energy measurement. Uncertainty in control of the laser pulse energy was about $\pm$0.25 mJ due to shot-to-shot laser variation.

4. Experimental Results

4.1 PETN Density and Specific Surface Area Effects

The graph of Fig 3 shows a typical range of laser energy required to provide PETN initiation. Threshold laser pulse energy is plotted versus PETN density for different specific surface areas of the explosive and for various thicknesses of titanium coating. This series of tests used a 15-cm focal-length lens to focus the laser output upon the explosive/coating surface. Light pulses with a near-Gaussian spatial distribution were used for all shot series except one, as noted in the figure. At a density of 0.90 g/cm^3, slightly more laser pulse energy was required for the detonation of MSSA PETN compared to that required for HSSA PETN. This was true whether no coat or a 2350-A Ti coat was applied to the confining laser window. It should be noted that since the relative standard deviation for this threshold data was typically about 10%, there is no discernible difference in threshold for the two types of PETN at a given density. In general, significantly greater laser energy was required for initiation without the presence of a light-absorbing coating.

Furthermore, the data of Fig 3 show a need for increased laser pulse energy as the density of the PETN is increased. For 1.00-g/cm^3 MSSA PETN, the lowest laser initiation energy was observed for samples with 2350-A Ti coatings. Increased laser energy was required to achieve threshold if a thinner Ti window coating of 1550 A were used or if the explosive was illuminated with multimode rather than Gaussian laser light.

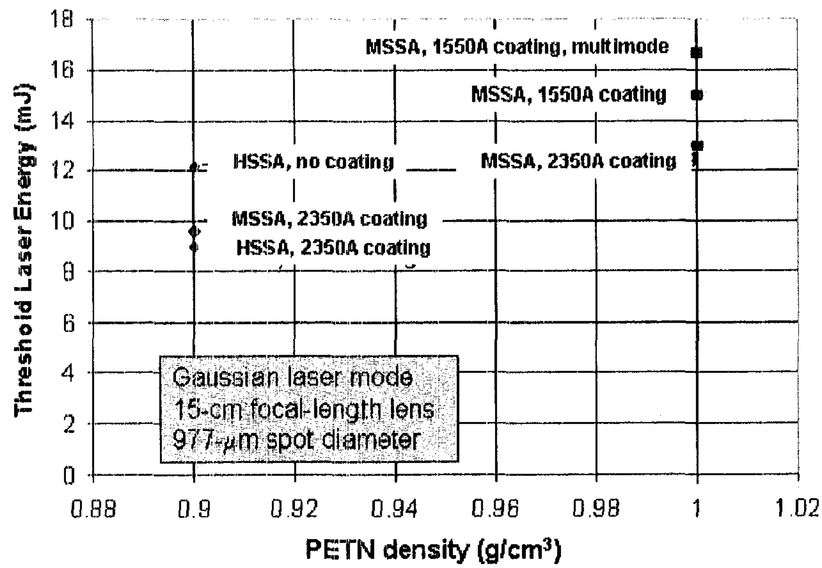

Figure 3. Threshold Laser Energy as Function of PETN Density

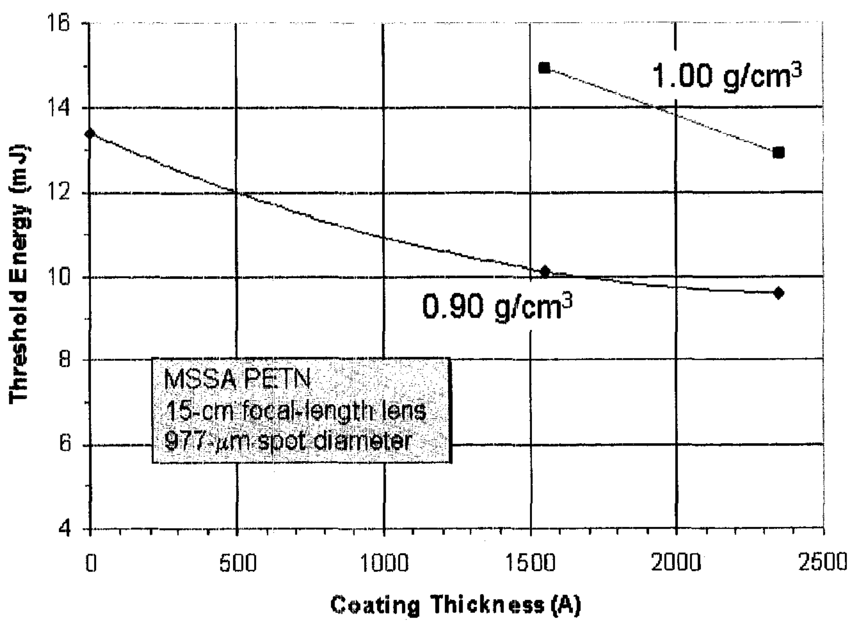

Figure 4. Threshold Energy for Various Metal Coating Thicknesses

The data given in Fig 4 show that increased laser pulse energy was required for initiation as the thickness of the metal coating was decreased for both 0.90 and 1.00 g/cm^3 densities of MSSA PETN. No detonations were obtained for the case of no coating at a 1.00 g/cm^3 PETN density, since required laser energy was greater than that available from the laser system (25 mJ) when operated with a Gaussian spatial mode.

4.2 Laser Spot Size Effect

The required threshold energy for PETN initiation as a function of laser spot size was also investigated. The results obtained for 0.90-g/cm^3-density MSSA PETN illuminated with multimode laser light of various spot diameters are shown in Fig 5. A 1550-Angstrom-thick Ti coating was applied to each of the laser window substrates used in these tests. Typically, threshold laser energy was minimal within a laser-spot diameter range of 520 to about 980 μm. At greater spot size, the required threshold laser energy increased sharply. The curve in the graph of Fig 5 is a quadratic fit to the data, showing the general trend of the data. Spot-size variation was achieved by use of lenses of various focal lengths in the range of 10 to 30 cm to illuminate the explosive/coating surface. Each lens was positioned one focal length away from the surface of the explosive. The 1-in-thick Plexiglas window of the explosive chamber caused some blooming of the laser spot at the surface of the explosive.

Interestingly, if the data of Fig 5 is replotted as a function of laser-illumination power density upon the target surface, a trend is seen in which decreased power density is required for initiation as laser light spot size was increased. A minimum power density of about 100 MW/cm^2 was required for a spot diameter of about 1000 μm, as shown in Fig 6. A knee in the threshold power-density curve was observed at about this spot diameter value. The solid line is a quadratic fit to the threshold data. These results depend upon our ability to accurately determine the effective laser spot diameter of the laser illumination upon the explosive. Although the beam profile was near Gaussian, we did not feel it was appropriate to characterize beam diameter simply in terms of the e-folding distance from the peak (i.e., P_{peak}/e). Instead, we used an option within our beam profiler software (manufactured by Spiricon Inc) to report the 90/10 point, where 90% of the energy was inside the reported diameter. This is believed to permit more appropriate comparisons of the effect opf beam profile on threshold firing energy. Laser spot sizes were measured with the thick explosive chamber window within the laser beam path. Work is continuing to more precisely characterize the laser-beam diameter.

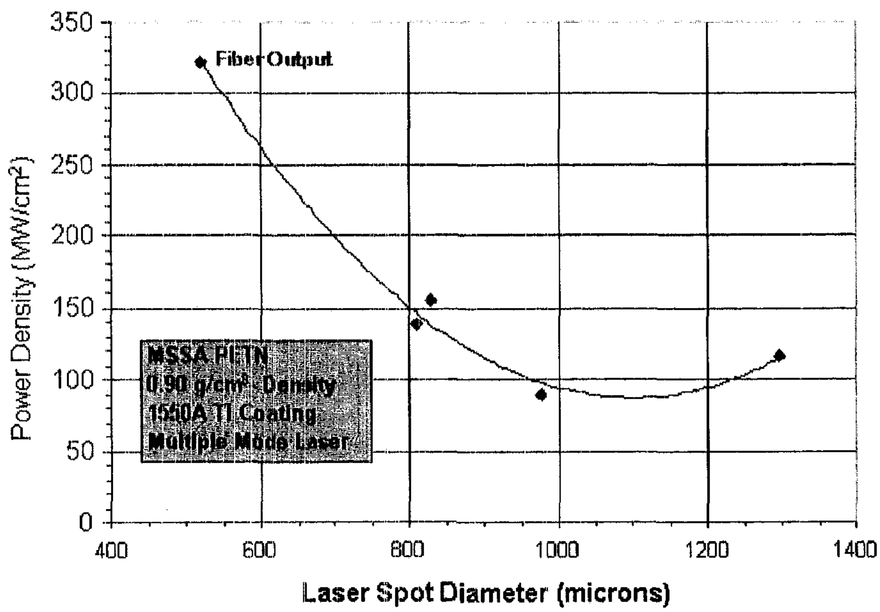

Figure 5. Threshold Energy Dependence on Laser Spot Diameter

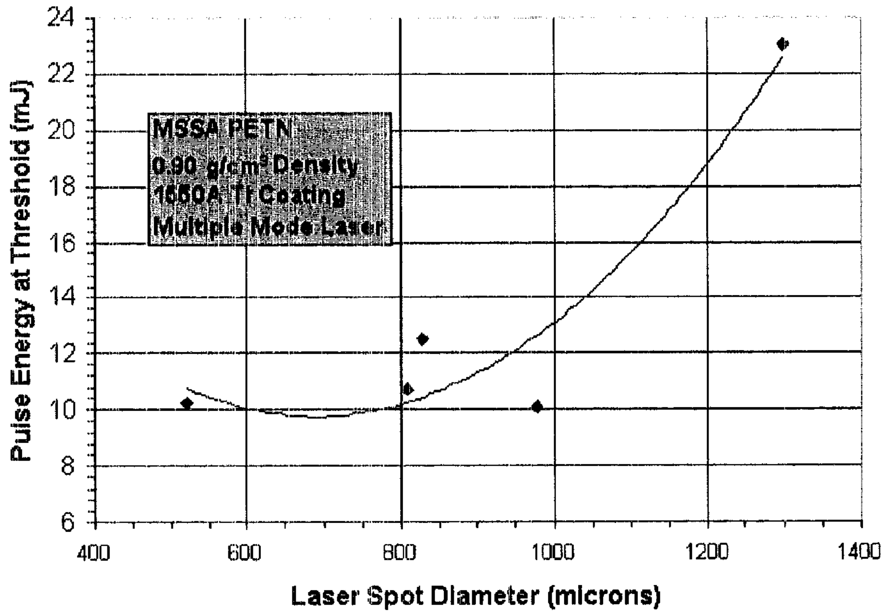

Figure 6. Threshold Laser Power Density as Function of Spot Size

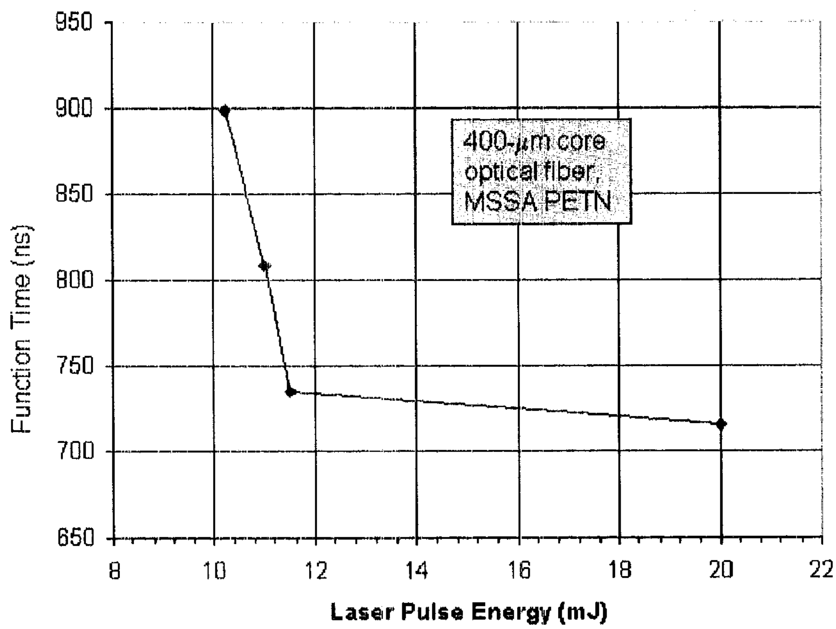

Figure 7. Function Time Decreases Asymptotically with Laser Pulse Energy

4.3 Timing Measurements

The promptness of detonation was also measured. A shock switch was used to monitor the time interval required for the detonation wave to become established and traverse the 2.23-mm-long explosive stack. Fiber coupling of the laser output was used during these measurements, providing a 520-μm-diameter, near top-hat laser light profile at the explosive surface. An oscilloscope used to monitor the shock switch waveform was triggered by the output of a fast photodiode, which detected the laser output pulse. The function time versus laser-pulse energy applied to the PETN is shown in Fig 7. Near threshold laser energy for explosive initiation (about 10 to 11 mJ for MSSA PETN using a 1550-A substrate coating), very large function times of more than 800 ns were measured. At pulse energy considerably above initiation threshold (20 mJ), the function time was reduced to about 720 ns. This value was still considerably greater than the 470 ns calculated for a steady detonation wave to traverse the explosive stack and for the driven shock wave to traverse the wall of the explosive cup.

5. Discussion of Results

We refer to the interval between the measured function time in these detonation initiation tests and the time required for steady detonation propagation as the excess transit time. Excess transit time was no less than 250 ns in these tests. The buildup process to full detonation thus appears to involve a significant fraction of the explosive length. Renlund[1] saw excess transit times in the 100-200-ns range, and interpreted her results to suggest that a deflagration-to-detonation (DDT) process occurs in direct laser initiation of detonation in low-density secondary explosives. We share that opinion because the excess transit time far exceeds the duration of the laser pulse and thus the duration of the input shock pulse. But data do not yet exist to demonstrate clearly that a DDT mechanism leads to the production of detonation.

As Yang and Menichelli[3] found, the initiation of low-density explosives was more efficient when a thin metal film was coated onto the window through which the laser light was introduced than when there was no coating. Our interpretation of that result is that organic explosive molecules allow light transmission and scattering to a significant depth in the explosive before a plasma is formed that is highly absorptive. On the other hand, the metal film is either reflective (e.g., aluminum) or absorptive (e.g., titanium) in the early stages of the laser pulse. Either of those characteristics produces more rapid formation of plasma, after which the metal-vapor plasma is highly absorptive. Thus coupling of laser power to the explosive material is more efficient with the presence of a thin metal film. The plasma from such a film is a relatively high in density, so it represents an effective piston for shock compression of the distended PETN pressing adjacent to it. Perhaps more importantly, the metal plasma consists of temporary gas that will readily condense upon cooling. Such condensation heat transfer can transfer heat to PETN crystallites extremely rapidly. This may provide a large kernel of reacting PETN as the source of combustion products driving a DDT process.

Our experiments showed that the efficiency of the initiation process increased with thickness of the titanium film on the window, within the range of values we used. Our maximum film thickness, 2350 Angstroms, was chosen because we believe that is the approximate thickness of metal ablated by the type of laser pulse we used. Recent work by Nagayama et al.[4] with 4000-Angstrom films of aluminum showed that a part of those films was driven off as solid particles, and their use of such a thick film did not enhance the initiation process. Thus our choice appears to have been about right.

It is interesting to compare direct laser initiation of PETN with exploding bridgewire (EBW) initiation of PETN. In EBW initiation of PETN, a fine wire is explosively vaporized due to rapid electrical heating by a capacitor discharge circuit, and the resulting plasma expands into low-density PETN that had been pressed into direct contact with the wire. In both processes, use of 0.90 g/cm^3 PETN is more effective than 1.00 g/cm^3 PETN, and use of finer PETN is a better choice than coarser PETN when the source size is small and the vaporization process is driven strongly. A small wire intended for EBW initiation might be considered to be 25 μm in diameter and 500 μm long. The volume of that wire is comparable to the volume of the titanium film that is vaporized in our experiments; both consist of about 200,000 μm^3.of metal. EBWs exhibit an excess transit time of approximately 100 ns and a run distance to detonation of about 1 mm. It may be that both EBW initiation and direct laser initiation of detonation take place through a DDT process. The minimum threshold energy we have obtained to date compares closely and favorably with the results of Renlund et al.[1], just under 10 mJ. That figure also corresponds closely to threshold firing energies for EBW detonators with small bridgewires.

6. Conclusions

These results confirm that direct laser initiation of PETN can be accomplished with sufficiently low energy and power density to permit fiber-optic transport of the laser firing pulse. This makes laser initiation a suitable candidate for design of detonators with enhanced safety properties, particularly in regard to electrical stimuli such as lightning. The most favorable design characteristics appear to involve a thin metal coating on a transparent window assembled adjacent to a low-density explosive pressing. Determination of the mechanism of operation of direct laser initiation of detonation will require a different type of experiment than the threshold experiments conducted in all studies to date.

We plan to conduct further work on this process.

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